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FINAL REPORT
INTERSTELLAR SCATTERING IMPLICATIONS FOR SETI DETECTION STRATEGIES

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OUTCOME OF CORNELL EFFORT

Work at Cornell focused on survey strategies and parameters that optimize the detection of ETI signals while taking into account propagation effects in the interstellar medium and in the solar wind. We have finished several short reports that discuss these effects. Much of the effort involved contributions from a graduate student at Cornell, Joe Lazio.

Some of our work was reported at a special meeting at NASA/AMES in 1994 January, organized by Jill Tarter in response to Carl Sagan's querys about the role of propagation effects on narrowband signals identified in Paul Horowitz's search at Harvard. Our work has centered on these questions and should provide answers relevant to the Horowitz/Sagan effort and to future work in SETI.

Joe Lazio and the PI have been working on several aspects of scintillations (ISS and IPS). These include:

(1) ISS and SETI in weak, moderate, and strong scattering. We have redone our search-optmization analysis for all three cases. The moderate (or transition) regime is interesting because the modulation is even stronger than in 'strong' scattering: the tail of the distribution extends much further than the exponential tail of strong scattering, so the interpretation of the Horowitz/Sagan 'events' would be different for a population of fairly close sources.

(2) ETI Source Populations and Scintillation-limited surveys: we've calculated log N-log S and 'V over Vmax' for ETI sources that are distributed either within a spherical volume or a disk-like volume. This has been done both without (ie the usual case) and with scintillations.

(3) A study of IPS expected as a function of stellar type: (along the lines of work presented at the Santa Cruz IWG meeting). We have modeled the solar wind and extended to other stars: while I think the solar wind's IPS can be mitigated against by staying with solar elongations > 60 degrees, I think all bets are off for host stars. Stellar mass-loss rates not much bigger than that of the Sun would imply IPS was imposed from the host star for planets in the habitable zone. Maybe the ET's are smarter than this and more technologically able, so they put their transmitters far away from the host star? Lot's to speculate on here but we should worry about ultra narrow spectral resolution.

NAG 2-697

(4) Probability of *multiple* detection vs. number of trials and the strength of scattering. If a signal has been boosted by ISS to make it detectable when it otherwise would not have been, it turns out that the probability of multiple detections in a large number of trials can be small or very small, depending on the amount of ISS boost. It's relatively easy to calculate the probability curves. For weak and transition scattering, we do this numerically from results in (1).

PAPERS

Papers written and submitted include:

Astrophysical Coding: A New Approach to SETI Signals. I. Signal Design & Wave Propagation, J.M. Cordes & W.T. Sullivan III, to be published in "Proceedings of the Santa Cruz Bioastronomy Conference," ed. S. Shostak, *Astron. Soc. Pac. Conf. Ser.*, 1995.

Astrophysical Coding: A New Approach to SETI Signals. II. Information About the Sender's Environment, W.T. Sullivan & J.M. Cordes, to be published in "Proceedings of the Santa Cruz Bioastronomy Conference," ed. S. Shostak, *Astron. Soc. Pac. Conf. Ser.*, 1995.

Search Methods for Interstellar Scintillating Sources: Weak and Transition Regimes, T.J. Lazio & J.M. Cordes, **ApJ**, submitted 1995.

ATTACHMENTS

Attached are three memos concerning scintillations and populations of ETI sources.

MEMO JMC.6

SCINTILLATIONS OF HOMOGENEOUS DISK AND SPHERICAL SOURCE POPULATIONS

James M. Cordes

November 1991; revised January 1994

I. Summary: I analyze searches for signals undergoing saturated (100%) interstellar scintillations that are transmitted from sources with homogeneous disk or spherical distributions. The optimum number of passes (trials) on each sky position is derived taking into account both scintillations and the distribution of source fluxes. The optimum is defined as the number of passes that maximizes the number of sources whose signal strengths exceed, at least once, a predetermined threshold. The optimum number of trials is 7 for disk populations and 6 for spherical populations. However, most of the benefit of multiple trials is achieved with 4 trials.

II. Homogenous Source Distributions

Consider homogeneous source populations that have planar disk or spherical distributions. The normalized source strength

$$r \equiv \frac{S}{I_T}$$

(where $S = g_A F$, g_A = antenna gain, F = flux density (as it would be without scintillations), and I_T is the intensity threshold for detection, defined in terms of the no-source radiometer noise) then has distribution

$$\frac{dn}{dr} \propto \begin{cases} r^{-2} & \text{disk} \\ r^{-5/2} & \text{spherical} \end{cases}$$

with constant of proportionality

$$C_r = \begin{cases} \dfrac{\eta h}{4}\left(\dfrac{g_A P}{I_T}\right) & \text{disk} \\ \dfrac{\eta}{4\sqrt{\pi}}\left(\dfrac{g_A P}{I_T}\right)^{3/2} & \text{spherical,} \end{cases}$$

where η is the density of sources (number/area or number/volume, respectively), P is the transmitter power (EIRP), and h is the scale height of the disk, assumed to be much smaller than the maximum distance probed.

Now consider the distribution of sources that are *detected* in a survey. We will ignore telescope beam effects by setting $g_A = 1$. Interstellar scintillations with 100% modulation (ie. strong scattering) are assumed to occur. In a single observation of a given sky position, the probability of detection for a source of strength $r = S/I_T \rightarrow F/I_T$ is simply the probability that the scintillation modulation exceeds r^{-1},

$$p_1 = \exp(-1/r).$$

Combining p_1 with dn/dr yields the distribution of *detected* sources:

$$\frac{dn_1^{(d)}}{dr} = \frac{dn}{dr} p_1.$$

These distributions maximize at normalized strengths $r_{max} = 1/2$ (disk) and $r_{max} = 2/5$ (spherical). In other words, the most-probable signal strength of *detected* sources is *below* the nominal, noise-derived detection threshold.

III. Distributions of Detected Sources

Now consider K trials on the same sky position, where each trial is statistically independent with respect to scintillations. This strategy is discussed in Cordes and Lazio (1991, 1993). The probability of one or more detections in K trials is, from the binomial distribution,

$$p_{\geq 1} = 1 - (1 - p_1^{\sqrt{K}})^K,$$

where the exponent $\sqrt{K}$ accounts for our assumption that the time per trial is T/K, so the total time per sky position is a constant T; the noise and, hence, the threshold I_T are assumed to scale as $(T/K)^{-1/2}$. The number distribution of detections is

$$\frac{dn_{\geq 1}^{(d)}(r, K)}{dr} = \frac{dn}{dr} p_{\geq 1}.$$

The cumulative distribution of all sources is

$$N(> r) \equiv \int_r^\infty dr' \, \frac{dn}{dr}$$

while the number of sources detected above a source strength r is, for single trials,

$$N_1^{(d)}(> r) \equiv \int_r^\infty dr' \, \frac{dn}{dr} p_1$$

and for K multiple trials is

$$N_{\geq 1}^{(d)}(> r, K) \equiv \int_r^\infty dr' \, \frac{dn}{dr} p_{\geq 1}.$$

IV. A Criterion for Survey Optimization

It is useful to define a normalized distribution

$$\mu_{\geq 1}(> r, K) \equiv \frac{N_{\geq 1}^{(d)}(> r, K)}{N(> r)}$$

that is unity if all sources that *exist* with source strength r or above are *detected* in the search. For small r (defined as those less than about unity), the search will miss some sources thus causing $\mu_{\geq 1}$ to fall below unity. A criterion for judging the optimum number of trials necessarily depends on some choice of r. In the absence of scintillations, $r \equiv 1$ is the intensity threshold above which all sources would be detected but for which there would also be a (small) multiple of false alarms. (That is, I_T defined above is a suitably large number of radiometer noise σ so that this is the case). When scintillations are included, the number of trials that maximizes $\mu_{\geq 1}(> r, K)$ at a ratio $r = 1$ is a sensible candidate for the optimum number of trials. This follows because (1) a lower value of r would increase the false alarm probability; and (2) a larger r would violate the specified survey sensitivity.

V. Results

Figure 1 Differential distributions for disk and spherical populations $dn^{(d)}_{\geq 1}(r, K)/dr$ and numbers of trials $K = 1, 2, 3, 4, 10$, and 100. The coefficient C_r is set to unity. Distributions are also shown (dashed line) for the noise-only case where scintillations have been 'turned off.' In this last case, only a single trial is considered and the noise is assumed to have an exponential p.d.f. (2 degrees of freedom). For larger degrees of freedom, the distribution will decline to zero much faster as r decreases below unity.

Figure 2 Cumulative distributions $N^{(d)}_{\geq 1}(> r, K)$ that are the integrals of distributions in Figure 1. Scintillations cause the number of detected sources to fall short of the actual number of sources.

Figure 3 Normalized cumulative distributions $\mu_{\geq 1}(> r, K)$ for disk and spherical populations. From these curves it is clear that the number of trials that optimizes sources of strength $r > 1$ is of order 5. Scintillations cause a sizable fraction of sources to be missed. However, a usable fraction of the many sources below the noise-only threshold ($r = 1$) will be detected *because* of scintillations.

Figure 4 $\mu_{\geq 1}(> r, K)$ for $r = 1$ plotted against K. The optimum value of K may be read off of these curves as 7 for the disk population and 6 for the spherical population. However, $K = 4$ trials achieves most of the increased rate of detection afforded by multiple trials.

VI. Conclusions

If ETI abounds in the galactic disk and transmits detectable signals from distances greater than the disk scale height, one should assume a source flux distribution corresponding to a disk population. Alternatively, signals detectable only from nearby stars comprise a spherical distribution. In either case, a survey strategy that incorporates multiple passes on a given sky position is needed to maximize the number of detected sources. Mathematically, the best number of passes is 7 (disk population) or 6 (spherical population) but only 4 passes are needed to achieve most of the benefit of this strategy. The multiple passes should occur at times that yield statistically independent interstellar scintillations.

References

Cordes, J. M. and Lazio, T. J. 1991, *Astrophysical Journal*, **376**, 123.

Cordes, J. M. and Lazio, T. J. 1993, 'Interstellar Scintillation and SETI,' in Proceedings of *Third Dicennial US-USSR Conference on SETI*, Astronomy Society of the Pacific, ed. G.S. Shostak 47, 143-159.

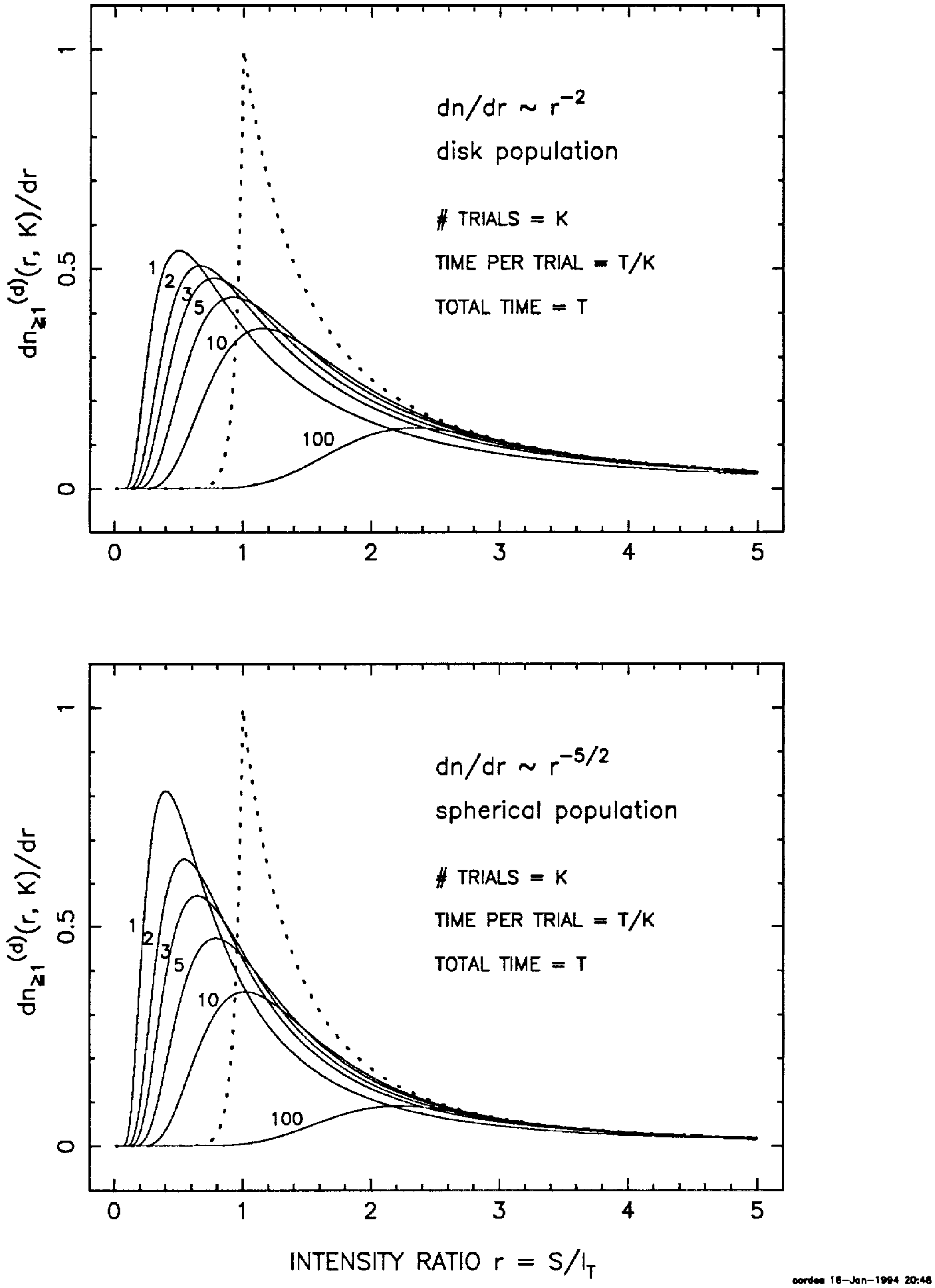


Figure 1: Differential distributions of detected sources plotted against normalized source strength (in units of the detection threshold I_T). The upper panel is for a disk population of sources while the lower panel is for a spherical population. (*Solid Lines*) The curves are labeled with the number of trials and take into account 100% interstellar scintillations. (*Dashed Line*) Same as the solid curves except that there are no scintillations, only additive noise.

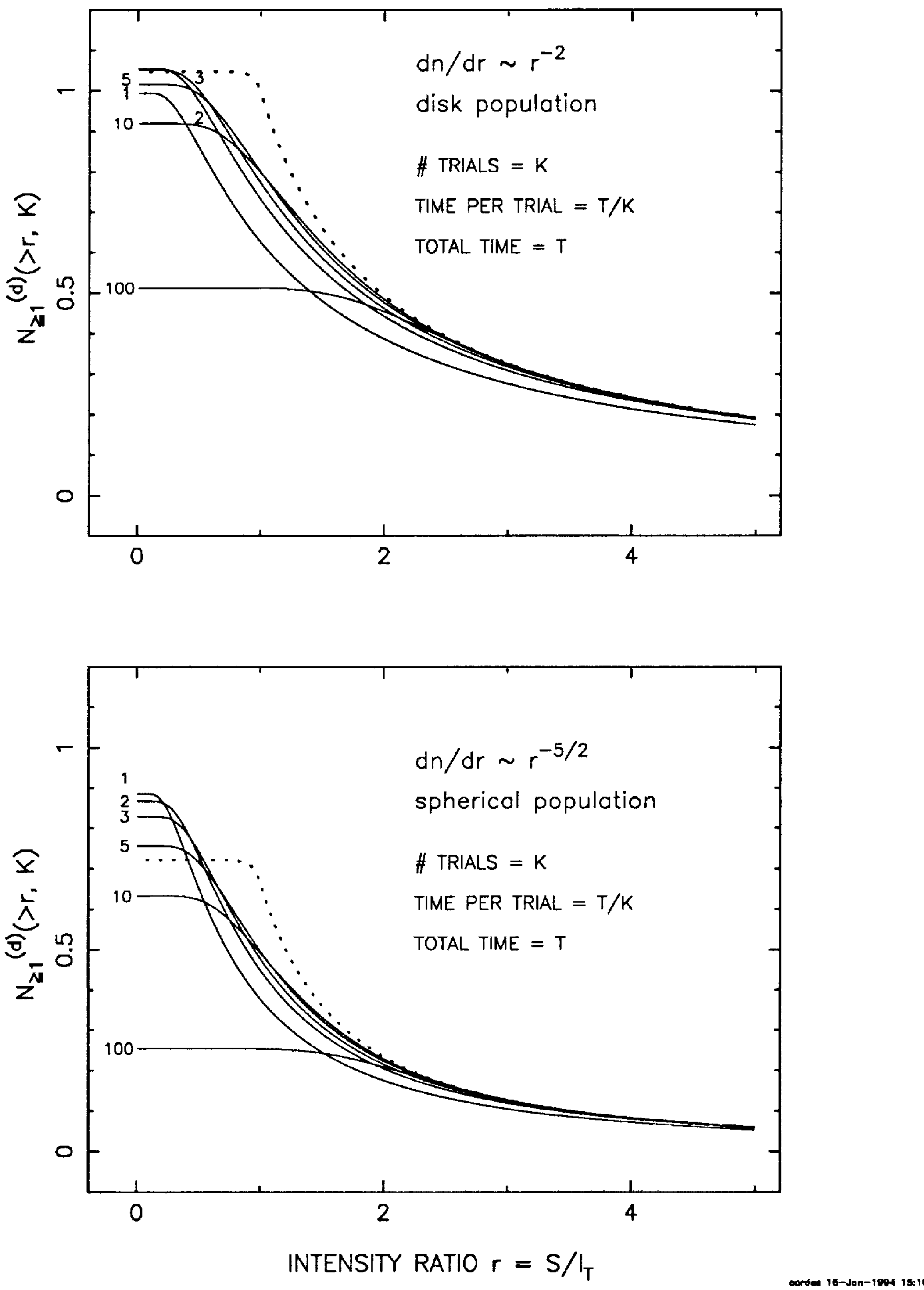


Figure 2: Integral distributions of detected sources.

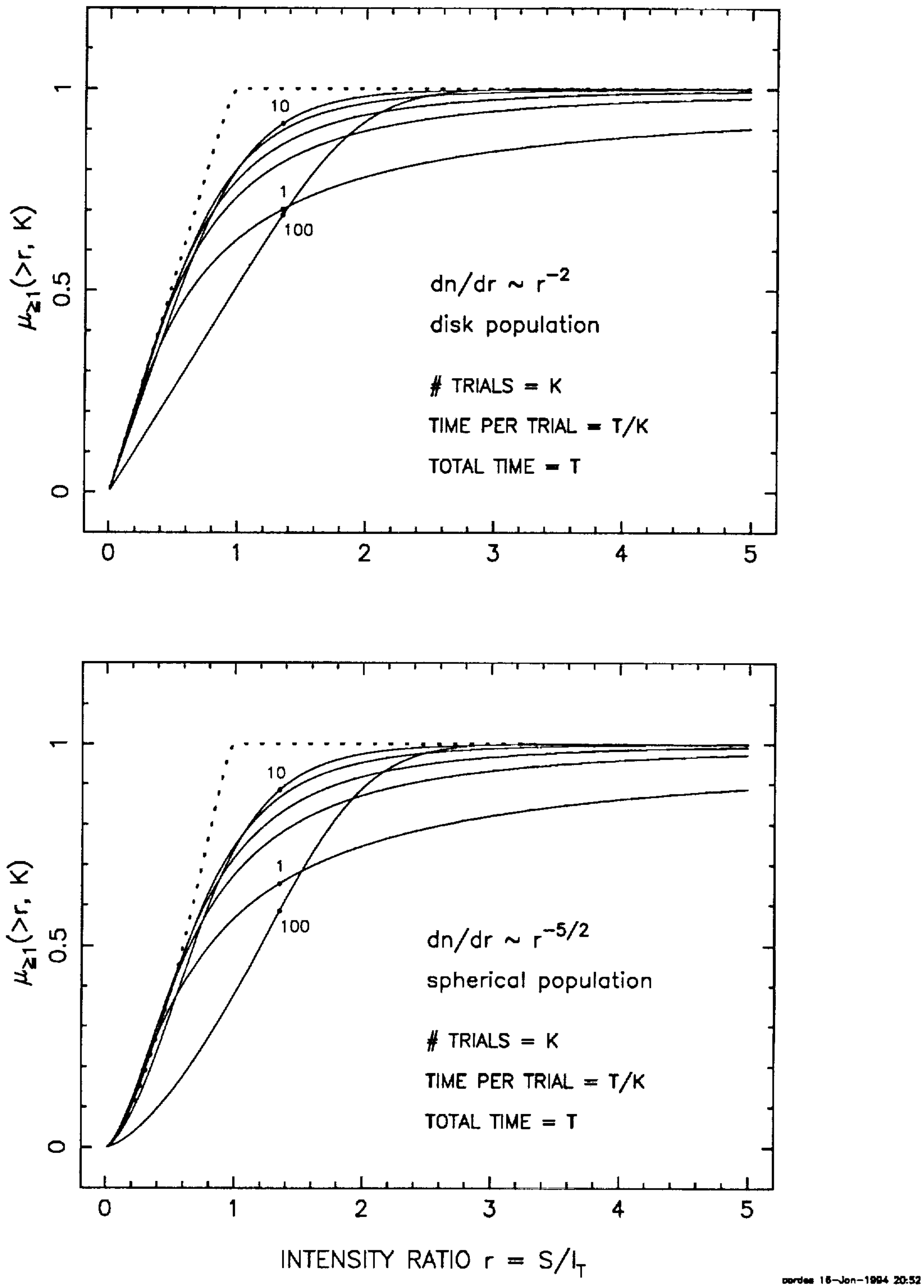


Figure 3: Normalized distributions of sources that are equal to unity if all sources that exist are detected. These curves can be used to define the degree of incompleteness of a survey when different numbers of independent trials are made. (*Solid Lines*) Scintillations included for $K = 1, 2, 3, 5, 10, 100$ trials. (*Dashed Line*) Noise only, no scintillations for one trial.

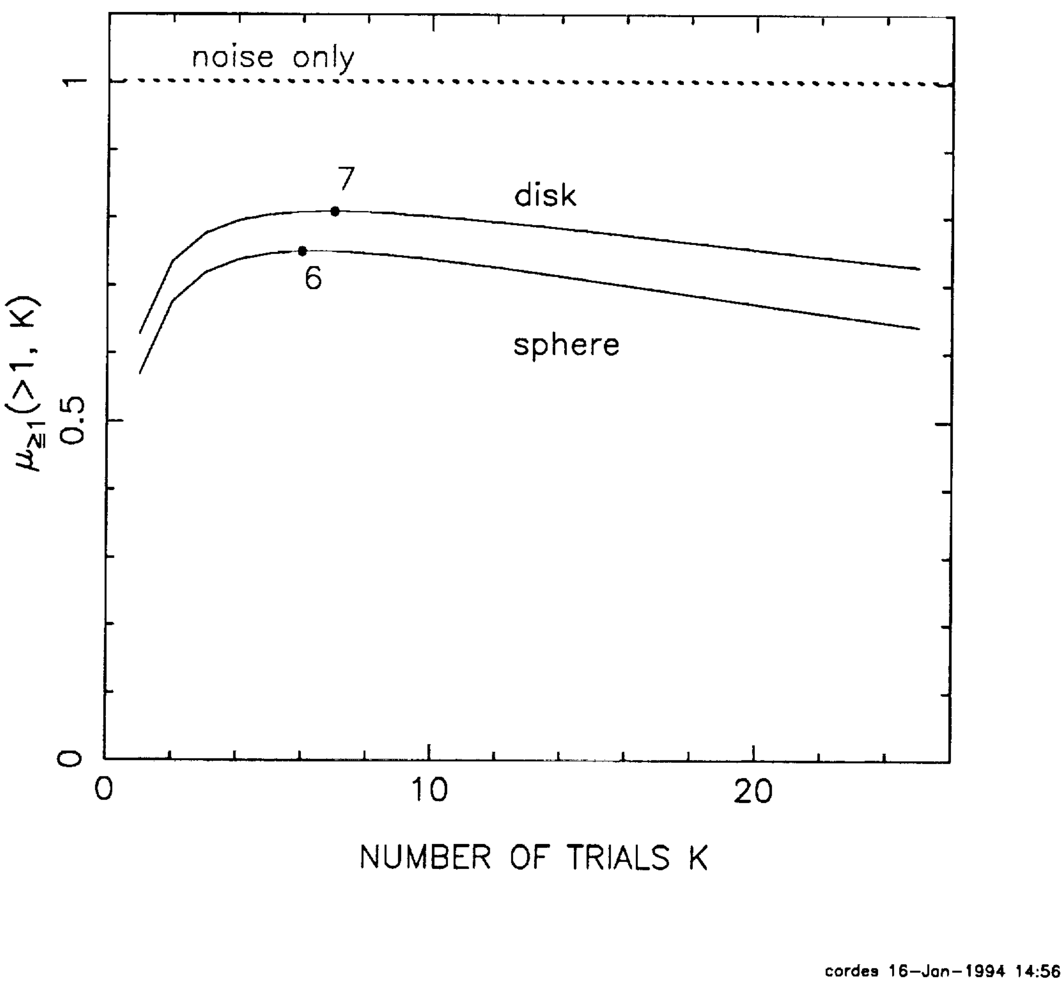


Figure 4: The normalized distribution of sources at $r = 1$ plotted against the number of independent trials. The maxima of these curves yield the optimum number of trials, 7 for a disk population, 6 for a spherical population.

MEMO JMC.7

V/V_{max} of SCINTILLATING, HOMOGENEOUS SOURCE POPULATIONS

J. M. Cordes

September 1993

I. Summary: We calculate the effects of saturated interstellar scintillations on the distribution of observed flux densities in a survey that makes a single pass on the sky. If the true distribution of flux densities has no cutoffs, then scintillations have no effect on the observed distribution. However, scintillations will extend a distribution with cutoffs by significant amounts. We show that the V/V_m statistic is also altered by scintillations for flux-density distributions that have cutoffs, such as might arise from a bounded population. Values for V/V_m of scintillating populations can range over the full interval of $[0,1]$ as a function of limiting flux density in a survey.

II. V / V_{max}

Consider a survey in which the minimum detectable flux density is S_{min}. If a source population of standard candles is assumed, then $S \propto D^{-2}$ and S_{min} corresponds to a maximum distance $D_{max} \propto S_{min}^{-1/2}$ and volume $V_{max} \propto D_{max}^m \propto S_{min}^{-m/2}$, where m is the dimensionality of the population. For disk and spherical populations, $m = 2$ and $m = 3$, respectively. Other flux densities S correspond to $V/V_{max} = (S/S_{min})^{-m/2}$. The average ratio of volumes over a differential distribution dn/dS is

$$\left\langle \frac{V}{V_{max}} \right\rangle = \frac{\displaystyle\int_{S_{min}}^{\infty} dS \left(\frac{S}{S_{min}}\right)^{-m/2} \frac{dn}{dS}}{\displaystyle\int_{S_{min}}^{\infty} dS \, \frac{dn}{dS}}.$$

It is well known that $\langle V/V_{max} \rangle = 1/2$ for unbounded, homogeneous populations. Scintillations alter apparent flux densities of sources but in such a way as to not change the shape of the source distribution dn/dS, unless there are cutoffs in the distribution due to boundaries. If there are boundaries, then scintillations alter the apparent distribution of flux densities and, thus, any average of V/V_{max} calculated from a measured sample.

III. Effects of Scintillations

Let the apparent flux be $S' = gS$ where g is the scintillation 'gain' or modulation whose p.d.f. in strong scattering is $f_g(g) = \exp(-g)H(g)$ where $H(g)$ is the Heaviside function. The distribution of apparent flux densities is

$$\frac{dn}{dS'} = \int dS \, \frac{dn}{dS} \left(\frac{e^{-S'/S}}{S} \right).$$

The resultant volume ratio is then

$$\left\langle \frac{V}{V_{max}} \right\rangle' = \frac{\displaystyle\int_{S_{min}}^{\infty} dS' \left(\frac{S'}{S_{min}}\right)^{-m/2} \frac{dn}{dS'}}{\displaystyle\int_{S_{min}}^{\infty} dS' \frac{dn}{dS'}}.$$

IV. Results

Figure 1 shows distributions dn/dS (unmodified) and dn/dS' (modified by scintillations) for the case where there are lower and upper cutoffs S_0 and S_1 to the intrinsic flux distribution (presumably due to a spatial boundary on the source distribution). Scintillations cause apparent flux densities to extend past these limits. The case shown is where $dn/dS \propto S^{-5/2}$, appropriate for a spherical population centered on the observer's position. The results are qualitatively the same for a disk population with $ds/dS \propto S^{-2}$.

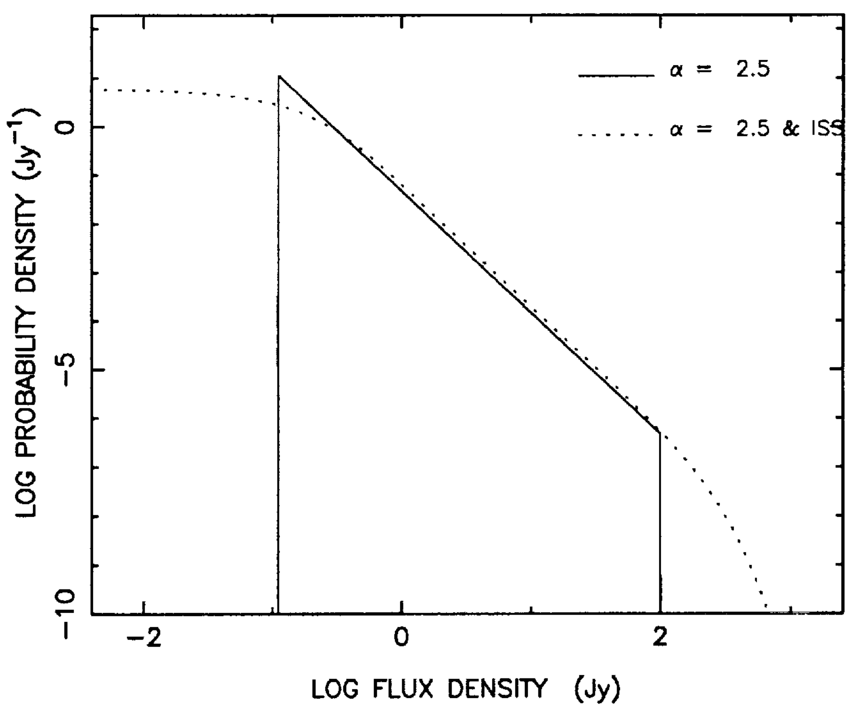


Figure 1: (*Solid Line*) Distribution of flux densities for a spherically distributed population of standard candle sources, but with spatial cutoffs (near and far) corresponding to flux density cutoffs. The case shown has a range of 10^3 in flux density. (*Dashed Line*) Distribution of apparent flux densities of sources that display saturated interstellar scintillations.

Figure 2 shows values of $\langle V/V_{max} \rangle$ as a function of S_{min}, the minimum detectable flux density in a survey. A nonscintillating population of sources will show the expected $\langle V/V_{max} \rangle = 0.5$ unless S_{min} becomes comparable to the upper flux density cutoff. The scintillating sample, if observed once and used to evaluate $\langle V/V_{max} \rangle$, will show strong departures from homogeneity at or beyond the cutoffs. More importantly, flux densities much smaller or much larger than the cutoffs will be present in the scintillating sample.

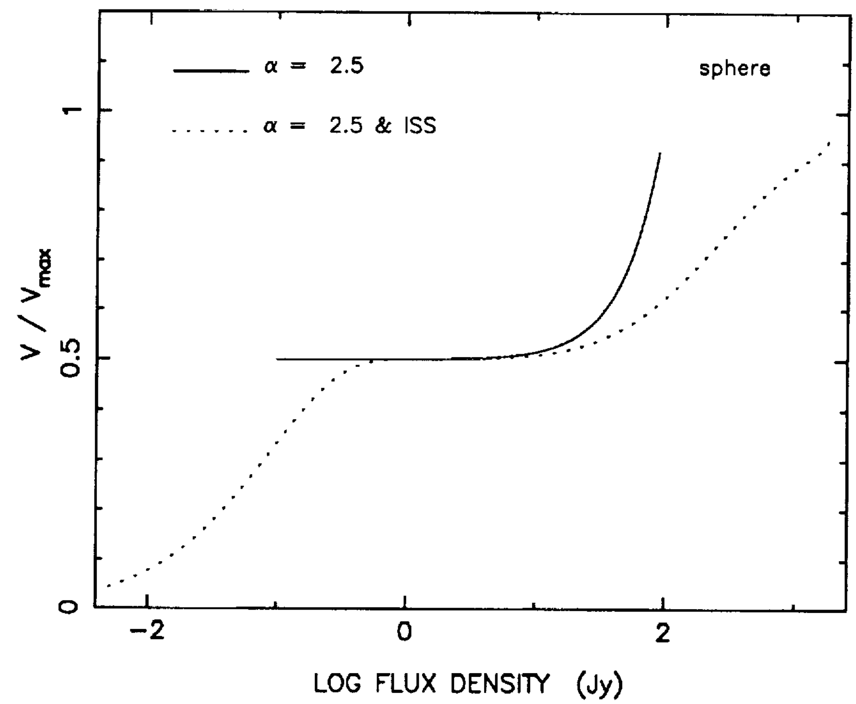


Figure 2: Plot of $\langle V/V_{max} \rangle$ for the source distributions in Figure 1 as a function of the minimum detectable flux density.

References

Cordes, J. M. and Lazio, T. J. 1991, *Astrophysical Journal*, **376**, 123.

Cordes, J. M. and Lazio, T. J. 1993, 'Interstellar Scintillation and Seti,' in Proceedings of *Third Dicennial US-USSR Conference on SETI*, Astronomy Society of the Pacific, ed. G.S. Shostak 47, 143-159.

Wasserman, I. 1992, *Astrophysical Journal*, **394**, 565.

MEMO JMC.8

MULTIPLE TRIALS VS. SINGLE TRIALS IN THE SKY SURVEY

Jim Cordes

25 August 1993

In studying the effects of interstellar scintillations on ETI sources, a primary conclusion has been that multiple observations are beneficial in maximizing the detection probability for a given sky position at a given frequency. This is true even for the case where the time alotted per sky position is held fixed and chopped into shorter observations. Sam Gulkis and Steve Levin have questioned whether the multiple-observation sheme should be implemented. As an alternative, they suggest that if no signal is observed in an initial observation of a sky position, then one may as well observe at a new sky position/frequency combination rather than reobserve the initial one. Here, I would like to comment on their suggestion.

If all sky positions ($\vec{\theta}$) and frequencies (ν) are considered equally probable, a priori, then one may as well observe a new $(\vec{\theta}, \nu)$ combination. *However*, the quoted survey sensitivity must take into account the fact that the detection probability is reduced significantly by scintillations. The Sky Survey currently quotes a sensitivity corresponding to a 90% probability of detection that is calculated in terms of radiometer noise only. When scintillations are taken into account (as usual, in strong scattering with 100% modulation and an exponential distribution), the probability curve is altered drastically because the *apparent* source strength is often less than the *mean* source strength. With scintillations, the detection probability is $p_d = \exp(-I_T/S)$ where I_T is the detection threshold and S is the mean source flux. Usually, I_T is many sigma (15 to 20). The mean source flux is what would be observed if there were no scintillations. Solving for the minimum source flux in terms of detection probability, $S_{min} = -I_T/\ell n p_d$, we find that a 90% probability requires $S_{min} = 9.5 I_T$.

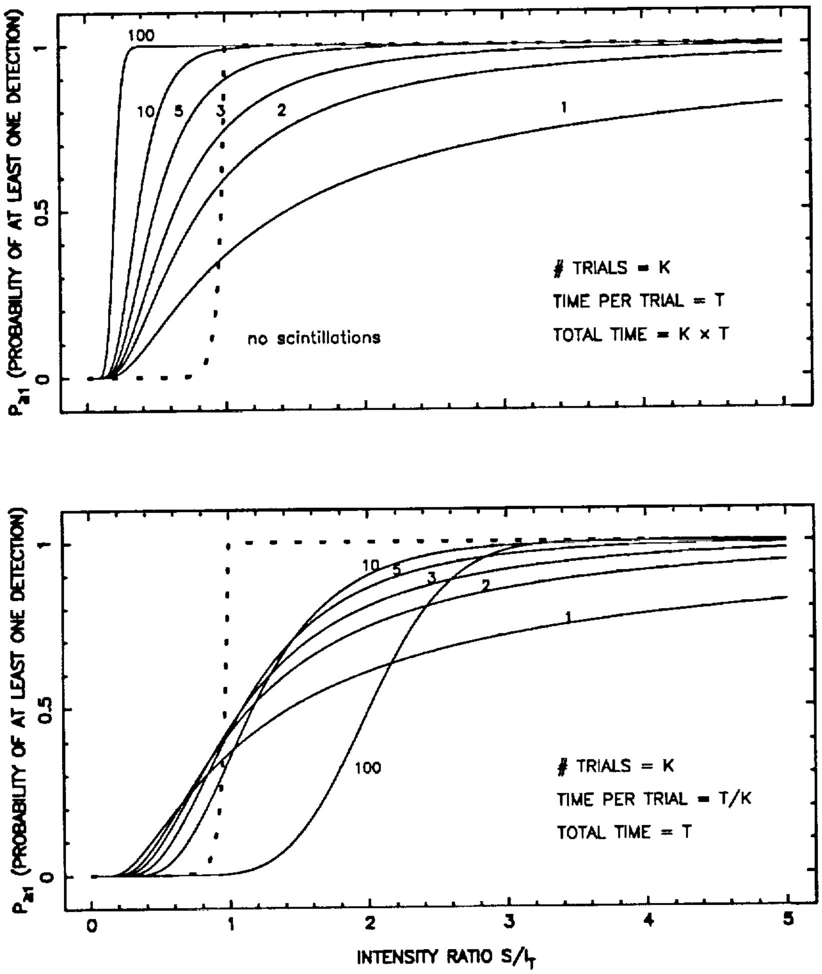
There are several courses to take:

(1) Redefine the survey sensitivity in terms of the *apparent* source sensitivity (ie. that modified by scintillations). This would be a cheat, of course, because the sensitivity would not be the same for sources of the same intrinsic strength at the same distance.

(2) Quote the survey's true sensitivity (in flux units) to be a factor of 9.5 higher than the value calculated on the basis of radiometer noise alone. (This would be a factor of 4.5 higher for 80% probability, 1.4 higher for 50%, and 19.5 higher for 95%).

(3) Make repeated observations of the same sky position to increase the detection probability. The attached curves show (top panel) the case where the original time per sky position is multiplied by the number of repeats and (bottom panel) the case where the total time is kept constant. The top curves apply for the Sky Survey because the time per source is determined by antenna slewing capabilities. To retrieve 90% probability of (at least one)detection at the nominal intensity threshold, at least 5 repeated observations are needed. Note also that with 5 repeats, the probability is above 50% for signal strengths $S > 0.5 I_T$, a net *gain* in sensitivity and observing volume of the survey.

My own preference is for case (3). I also would favor concentration on the galactic plane though I do not favor any 'magic' frequencies.



(*Top*) Probability of at least one detection in K trials, each of duration T, plotted against the ETI source strength S in units of the detection threshold I_T. The dashed line would apply if no scintillations occurred and is evaluated for exponential noise statistics (2 degrees of freedom) and a false-alarm probability at $S = 0$ of 10^{-9}.

(*Bottom*) Similar to top frame, except the duration of each observation is now T/K, so the total time is equal to T, no matter how many trials. It may be seen that, for fixed S/I_T, there is an optimum number of trials that maximizes the probability. At $S/I_T = 1$, for example, the optimum number is $K = 4$.